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# Comparison of Algorithms for Synthesizing Weather Avoidance Routes in Transition Airspace

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**This paper investigates the problem of synthesizing weather avoidance routes in the transition airspace – from approximately 200 nmi range to the metering fixes of an airport. The problem is motivated by the desire to maximize the capacity of today's airspace. The future of the National Airspace System (NAS) requires that airports accommodate greater capacity, and the hazardous weather avoidance problem is perhaps one of the most challenging limiting factors. Three methods are compared to current-day operations. Emphasis is placed on a comparison of the arrival traffic weather avoidance routing and metrics associated with such routes. Actual weather avoidance paths (baseline) are compared to three types of solutions: variations of the Standard Arrival Routes (STARs), a geometric optimization solution synthesizing multiple non-intersecting routes, and a Free Flight approach in which aircraft fly weather avoidance routes using a "greedy" prioritization method. The solutions indicate that increases in capacity over today's NAS are achievable, but they are limited by the method, the required supporting infrastructure, and the severity of the weather.**

## Nomenclature

| | | |
|---|---|---|
| AAR | = | Airport Arrival Rate |
| ATC | = | Air Traffic Control |
| ATL | = | Atlanta Hartsfield International Airport |
| dBZ | = | decibels |
| FBRP | = | Flow-Based Route Planner |
| MIT | = | Miles-In-Trail |
| NAS | = | National Airspace System |
| Navaid | = | Navigation Aid |
| NCWD | = | National Convective Weather Diagnostic |
| Nmi | = | Nautical Mile |
| NWS | = | National Weather Service |
| SID | = | Standard Instrument Departure Route |
| STAR | = | Standard Arrival Route |
| VIL | = | Vertically Integrated Liquid |
| $\mu$ | = | Statistical Mean |

## Introduction

AIR Traffic Control (ATC) in the airport transition airspace works well under normal operating conditions. However, under inclement weather, the reduction in available non-convective airspace limits capacity, and throughput is adversely affected. The Aviation Capacity Enhancement Plan[1] lists weather as the leading cause of

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delays greater than 15 minutes, with terminal volume as the second leading cause. As shown in Figure 1, weather-related delays, which have steadily increased in the summer convective weather seasons prior to Sept. 11, 2001, are likely to get worse as the volume of air traffic increases in the future.

While the weather has not fundamentally changed over the years, delays have steadily increased because there have been greater demands on limited resources. Furthermore, those resources experience significant capacity reductions during weather events. This is because aircraft in neighboring flows adversely affect each other while they perform weather avoidance maneuvering – indeed, the maneuvering that is performed is typically "reactive" to avoid hazardous weather cells and is not designed to be optimal in any way. Safety constraints dictate that the aircraft must remain separated from one another as well as from hazardous weather. As aircraft deviate around weather, they deviate from the preferred direct-to route, but they also require neighboring aircraft to "keep out of their way" (ATC provides the function of safely separating aircraft). Thus, neighboring aircraft are typically spaced out at greater distances behind a leading aircraft in a flow, as ATC increases the mandated Miles-In-Trail (MIT) between aircraft, thereby adding to the delays experienced during weather avoidance situations. Thus, not only are aircraft delayed due to a path stretching effect of weather avoidance maneuvering, they are also delayed due to MIT restrictions imposed during weather events.

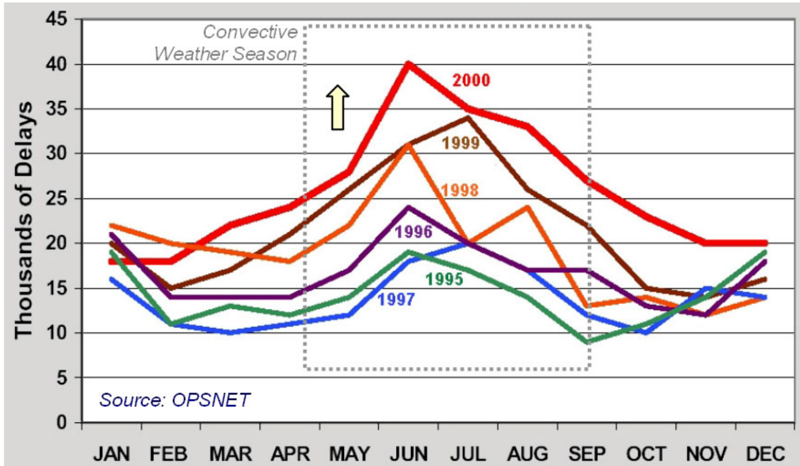


**Figure 1: Yearly trends (1995-2000) for weather related delays.**

This paper compares several solution approaches to synthesizing (by computer automation) weather avoidance maneuvers in the transition airspace. The problem is solved for the transition airspace, within a roughly 200 nmi range to the metering fixes of an airport. Using the current National Airspace System (NAS) operations as a baseline, solution paths from three new algorithmic approaches are compared:

1. Variations on the Standard Arrival Routes (STARs) – the navigation aids (Navaids) that constitute the STARs of an airport are varied by a set amount of lateral separation to design a new STAR as a function of time of day that safely avoids hazardous weather. Aircraft are metered at the 200 nmi range ring.
2. Flow-Based Route Planner (FBRP) – Multiple, non-intersecting routes are designed to lead from the 200 nmi range ring to the airport metering fixes. Multiple routes are synthesized for each metering fix, based on maximizing the total number of routes that both avoid hazardous weather and do not cross over each other (thus, do not allow aircraft to violate separation standards). Given a set of routes leading to the metering fixes, the route that minimizes the distance traveled, subject to various constraints, is chosen for each aircraft. Aircraft are metered (using speed control) so that only one aircraft arrives at the metering fix at a time, regardless of the weather avoidance route chosen.
3. Free Flight – Free Flight routes are synthesized such that the routes do not cross over hazardous weather and do not create separation conflicts with any aircraft already ahead of an aircraft in the transition airspace. The algorithm is "greedy" in the sense that each aircraft acts independently, selecting a best safe path between the 200 nmi range ring and the metering fix, subject to the constraints imposed by earlier aircraft arriving to the airspace. Separation requirements implicitly create the metering of aircraft.

As a part of our problem statement, there are several assumptions that are briefly mentioned at this time. We only compare arrival routes, and do not analyze the coupling of arrival routes and departure routes; nonetheless, our solution approaches are easily applied to the problem of synthesizing arrival and departure routes simultaneously. For instance, the same algorithm that is used to design variable STARS can be used to design variable Standard Instrument Departure Routes (SIDS). Furthermore, we do not investigate the synthesis of weather avoidance routes from the metering fixes to the runways. These routes can be synthesized using similar approaches to those that are applied here to the transitional airspace; see the work of Krozel[2] et al for an algorithmic solution. Finally, we do not address vertical separation issues, since real-world data suggests that the arrival and departure routes can be separated to different flight levels based on standard arrival descent profiles and standard departure climb profiles that can be designed to avoid vertical conflicts.

A number of approaches to synthesizing weather avoidance routes are found in the literature. Several approaches apply an "optimal" path algorithm based on grid search methods[3,4,5,6,7]. The problem can be formalized as a "weighted regions problem" in which routes obey Snell's Law of refraction[4,8,9] as a local optimality criterion. Algorithms can exploit the fact that optimal routes bend at boundaries between regions of varying weather severity in analogy with light rays that refract as they pass through regions of varying refractive index[7,10]. Another related approach[2] allows one to search for paths having at most $k$ turns (waypoints), while avoiding hazardous weather, thereby bounding the workload of the pilot and controller required to track the solution.

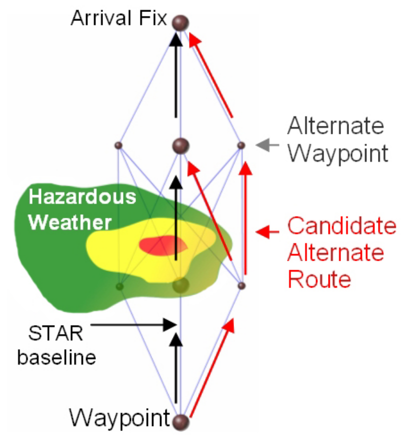


**Figure 2: Alternate weather avoidance waypoints relative to STAR waypoints.**

## Weather Avoidance Algorithms

Next, we describe briefly the algorithms used to synthesize weather avoidance routes for this paper.

### A. Variable STARS

As shown in Figure 2, the Variable STARs method creates alternate routes around hazardous weather using the STARs as a baseline and waypoints that are varied within a fixed lateral separation from the STAR. The underlying graph (Figure 3) is defined by waypoints, where each vertex in the graph is a STAR Navaid plus or minus a fixed lateral offset. The graph is searched using an A* algorithm[11] to determine an optimal weather avoidance path.

A major benefit of this method is that the lateral offsets may be communicated easily between controllers and pilots (verbally or with automation), and the familiarity with the SID and STAR Navaids is not lost. The method maintains close similarities with current ATC operations while providing some automation to hazardous weather avoidance. A limitation of this method is that planned routes may have no choice but to penetrate hazardous weather. In such a case, aircraft are restricted from using the planned route until the algorithm considers the next interval of time and synthesizes another route avoiding hazardous weather. This leads to delays assigned upstream and route closures in application. MIT restrictions of 8 nmi consistent with current-day standards (5 nmi required + 3 nmi safety margin) are maintained at the 200 nmi range ring.

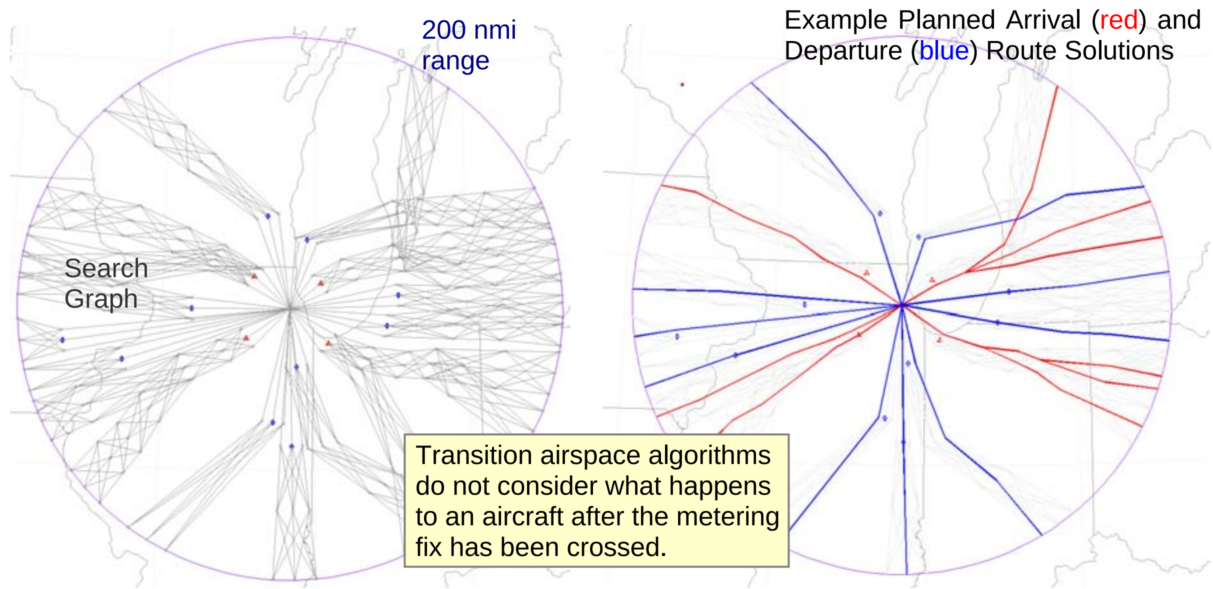


**Figure 3: The ORD weather avoidance search graph based on SIDs and STARs.**

### B. Flow-Based Route Planner (FBRP)

The FBRP algorithm, described in Prete and Mitchell[12], determines if there are one, two or three non-intersecting weather avoidance routes that lead from the 200 nmi range ring to the metering fix location. Each single route is partitioned into a set of flows having short time gaps between their respective arrival time windows, in order to account for any MIT restrictions. The creation of multiple non-intersecting routes in multiple flows adds another layer of complexity to the algorithm, since separation standards must be enforced. The algorithm computes multiple routes incrementally, enforcing separation standards with respect to each route already in place. Since conflicts can arise between already routed flows and flows yet to be routed, it is necessary to search among several possible orderings of routes, in order to find solutions to all routes (if such hazard-free routes exist). Note that while potentially all three routes may be in use, by the time aircraft arrive at the metering fix, they will have been controlled by speed to be separated by 8 nmi apart. Thus, at the metering fix a continuous flow of aircraft is achieved even though the aircraft may be using different routes to arrive at the metering fix. Figure 4 illustrates an example solution from this algorithm.

### C. Free Flight

The Free Flight algorithm (Figure 5) is designed to synthesize routes that enable individual flights to be routed conflict-free and clear of dynamic, hazardous weather constraints. As each flight arrives at the 200 nmi boundary, it is individually routed to the arrival metering fix corresponding to its quadrant of entry. The optimal path of each aircraft is routed without regard for how the decisions of the aircraft might adversely affect upstream aircraft (e.g., a non-optimal sequence). The solution is designed to mimic a distributed system where each aircraft non-cooperatively plans its own route.

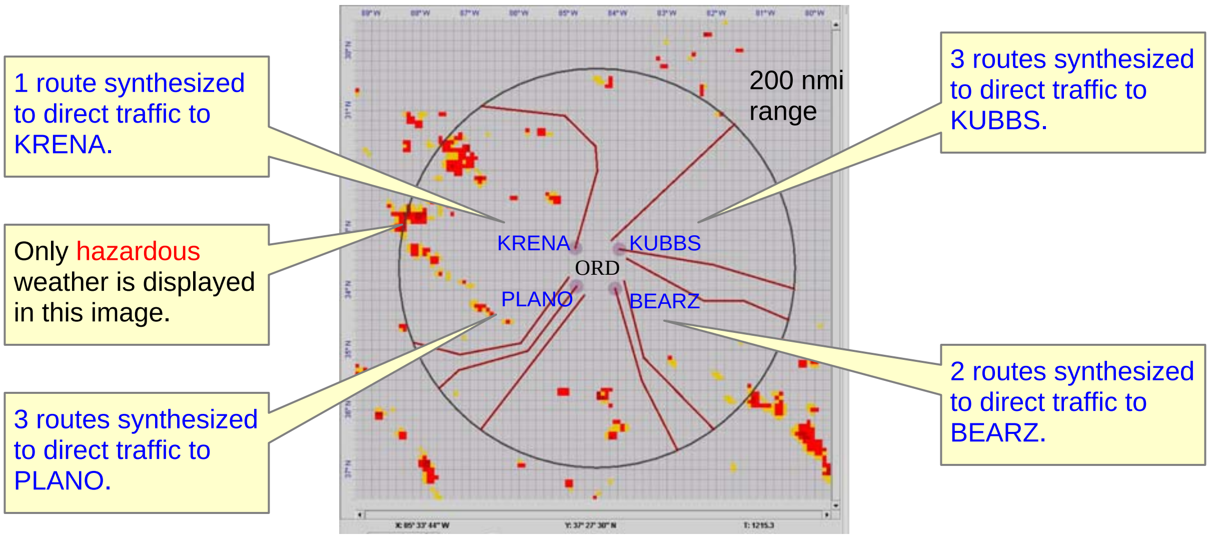


**Figure 4: The ORD weather avoidance search identifies non-intersecting routes that direct independent flows from the transition airspace boundary to metering fixes.**

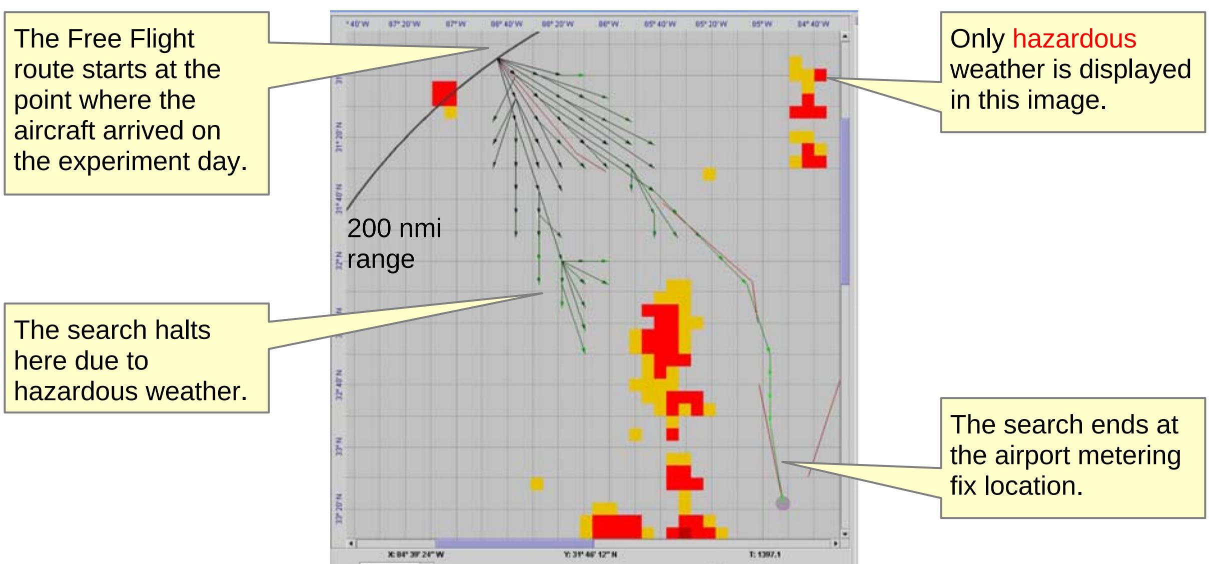


**Figure 5: A search identifies the optimal Free Flight route avoiding hazardous weather.**

The Free Flight algorithm uses a search in space-time (as in the Space-Time Flow method[13]), treating already routed flights as constraints to be avoided (according to the minimum separation standards between aircraft), along with severe weather constraints, no-fly zones, and quadrant constraints (confining an aircraft to the quadrant initially entered).

Free Flight routing allows maximum flexibility in terms of individual aircraft routing; however, by allowing each flight to be greedily routed, the Free Flight solution can result in some routes being particularly efficient, at the expense of blocking off a passage for other flights. Furthermore, there is no attempt in the Free Flight algorithm to sequence aircraft optimally.

## Comparison

National Convective Weather Diagnostic (NCWD) data is generated from radar Vertically Integrated Liquid (VIL) data and lightning data over the United States. The hazardous weather coverage of the region was recorded for the experiment dates 5/22/02, 6/26/02 and 6/27/02. This hazardous weather coverage was simply the percent of area that is NWS Level 3 (Table 1) or higher relative to the total area recorded for a rolling 30-minute time period. A 30-minute time period is used because it is the approximate time it takes for an aircraft to travel from the 200 nmi range to the metering fix. For experiments with a 15-minute update time, this essentially translates to a 45-minute look-ahead at the predicted weather. An example of the severe weather coverage is shown in Figure 6. Ranges of the severe weather coverage were given qualitative labels for use in discussion.

Optimal routes were generated on the search graphs generated from the STARs and SIDs for each of the experiment scenarios. The algorithm assigned a cost to the routes based on the maximum weather present from the current time to the next re-planning update time plus 30 minutes (for the approximate travel time). To ensure safety, a candidate route was closed completely if hazardous weather (NWS Level 3 or above) intersected any part of it. The lateral offset for the alternate waypoints varied from 8-16 nmi as the route extended further from the airport. The following parameters were varied:

- Re-planning Update Time: 10, 15, 20, 30 minute re-plan updates
- Severe Weather Safety Margin: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 nmi safe distance from hazardous weather.

The re-planning update time is the time that each route is active before a new route may be generated. All results (Figure 11 to Figure 18) are shown with 15-minute update times and a minimum 1 nmi weather separation.

**Table 1: NWS Standard reflectivity levels and weather classifications.**

| NWS Level | Color | Rainfall Rate (mm/hr) | Reflectivity (dBZ) | Type |
|---|---|---|---|---|
| 0 | None | <0.49 | dBZ<18 | None |
| 1 | Light Green | 0.49 - 2.7 | 18≤ dBZ<30 | Light Mist |
| 2 | Dark Green | 2.7 - 13.3 | 30≤ dBZ <41 | Moderate |
| 3 | Yellow | 13.3 - 27.3 | 41≤ dBZ <46 | Heavy |
| 4 | Orange | 27.3 - 48.6 | 46≤ dBZ <50 | Very Heavy |
| 5 | Deep Orange | 48.6-133.2 | 50≤ dBZ <57 | Intense |
| 6 | Red | >133.2 | 57≤ dBZ | Extreme |

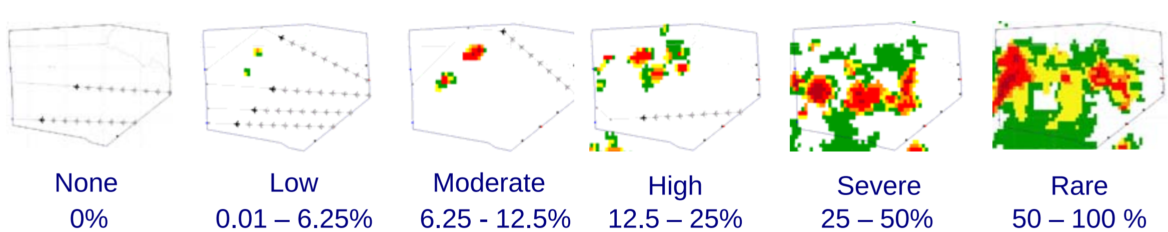


**Figure 6: Classification of weather coverage level by sector area.**

The FBRP algorithm was run using three routes per metering fix. The following parameters were varied:

- Lateral Separation: 2, 4, 6, 8 nmi between routes
- Re-Planning Update time: 10, 15, 20, 30 minute re-plan updates
- Severe Weather Safety Margin: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 nmi safe distance from hazardous weather

For the sake of comparison with the variable STAR approach, a lateral separation of 8 nmi was used. All results (Figure 11 to Figure 18) are shown with 15-minute update times and a minimum 1 nmi weather separation.

The Free Flight routes were generated by using the historical flight data as a basis for the starting positions and cross times for flights at the 200 nmi range. The separation requirement for aircraft was set at 5 nmi (for both lateral separation and MIT). The following parameter was varied:

- Severe Weather Safety Margin: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 nmi safe distance from hazardous weather

The resulting routes for the flow-based methods were processed using a scheduling algorithm. The flights were scheduled to the route entry points (at the 200 nm range) and then at the metering fixes, given a speed profile based on historical data and a required 5 nmi separation at the metering fixes. Flight metrics were computed by simulating flights on those routes and comparing with statistics gathered from historical flight data. Flights generated in the simulation are based on initial conditions that match the crossing times and positions of historical flights. Speed profiles for the aircraft were based on historical data to approximate the effect of winds. In the flow-based techniques, it is assumed that flights are organized and routed before arriving at the 200 nmi range so that they arrive on the synthesized routes. In the Free Flight approach, the flights arrive along the 200 nmi range based on historical demand and must self-organize (each aircraft is not allowed to violate the airspace already used by upstream aircraft) into a flow over the metering fix within the transition airspace.

The focus of the experiments was on the Atlanta Hartsfield International Airport (ATL). ATL executes a standard 4-cornerpost fix arrangement and is a major hub with significant throughput. This allowed generalization of results, while still giving the ability to compare with historical data. Today, ATL's typical clear-weather Airport Arrival Rate (AAR) is about 100 arrivals per hour, but this rate is significantly reduced when severe weather is present. Algorithmic solutions were generated for the following time periods:

- ATL 5/22/2002 12:00-23:59 Z (8 am - 8 pm local time) (Clear to Light Weather)
- ATL 6/26/2002 12:00-23:59 Z (8 am - 8 pm local time) (Light to Severe Weather)
- ATL 6/27/2002 12:00-23:59 Z (8 am - 8 pm local time) (Light to Severe Weather)

To investigate a comparison between weather avoidance algorithms implemented in today's (2002) capacity situation at individual metering fixes (4 metering fixes each for ATL), the same initial conditions were applied to the following:

1. Real-World Data (Demand Baseline) – defines the initial conditions at the transition airspace boundaries and the baseline statistics for real-world weather avoidance routes; all other techniques use the same initial conditions but synthesize weather avoidance results.
2. SID/STAR-based graphs (2 routes per metering fix).
3. Flow-Based Route Planner (3 routes per metering fix).
4. Free Flight (each aircraft self optimizes to 1 metering fix).

In all cases, the algorithms are forced to adhere to the required minimum separation of 5 nmi over the metering fixes. FBRP flows utilizing 2 or 3 routes to a single metering fix must be merged at or before the metering fix. For the flow-based routes, this is enacted through the scheduling algorithm during the simulation of flights on the routes. Therefore, it has no effect on the generation of routes. For the Free Flight approach, this separation requirement at the metering fix is a result of the constraint that aircraft maintain 5 nmi separation at all times.

Output metrics were used to compare between each of the transition area weather avoidance algorithms, thus providing an equivalent basis for comparison. Throughput was measured at the metering fixes. This was computed as the number of aircraft crossing the metering fixes (calculated at the closest point of approach to the metering fix). Weather penetration was calculated as "true" or "false," given a specified clearance (safe-distance) from hazardous weather (NWS Level 3 or above). To insure safety as a constraint in the algorithms, weather penetration was required to be 0 for any specified weather clearance. Complexity was measured as the number of changes in each aircraft's nearest neighbor. Thus, a uniform flow of aircraft following each other one after another would be very low complexity, aircraft following distinct weather avoidance routes (flow-based or Free Flight) would potentially be a higher complexity, and a set of aircraft all flying in different directions would be the highest complexity.

In addition to simulations based on historical flight data, simulations were run to estimate the maximum possible throughput given a constant demand (rather than a fluctuating historical demand). These simulations were run for the same time periods, with identical hazardous weather data.

## Results

The first point to be made is with respect to safety. The algorithmic approaches investigated in this research guarantee that no hazardous weather is penetrated. Otherwise, no solution is reported by the algorithm. As illustrated in Figure 7 and Figure 8, historical flights did not always adhere to this restriction. Research[14] confirms that as pilots get closer to metering fixes, there is a greater chance that the pilot will choose to penetrate NWS Level 3 (or above) weather cells. There was also a lack of data for cloud tops, which would indicate when flights were capable of flying over certain storm systems. The ideal input set of severe weather data would include not just reflectivity and cloud-to-ground lightning strikes, but also cloud tops, cloud-to-cloud lightning strikes, clear-air turbulence, or any other constraints that make the airspace unusable by aircraft.

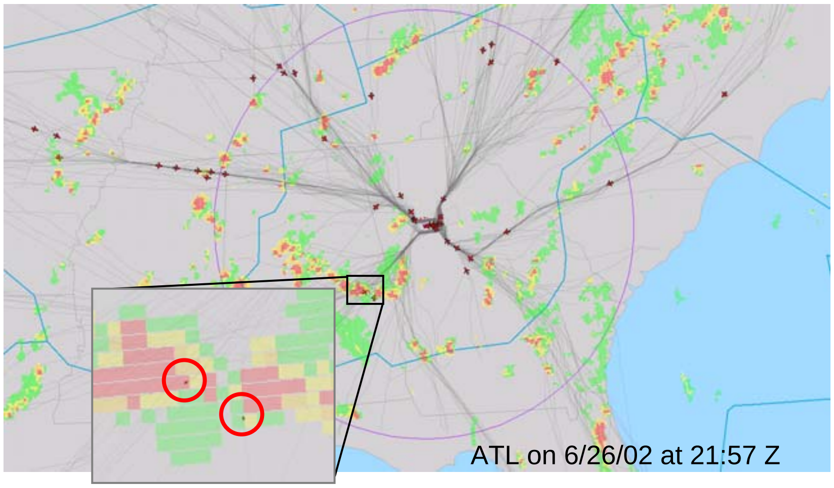


**Figure 7: Historical flights penetrating hazardous weather.**

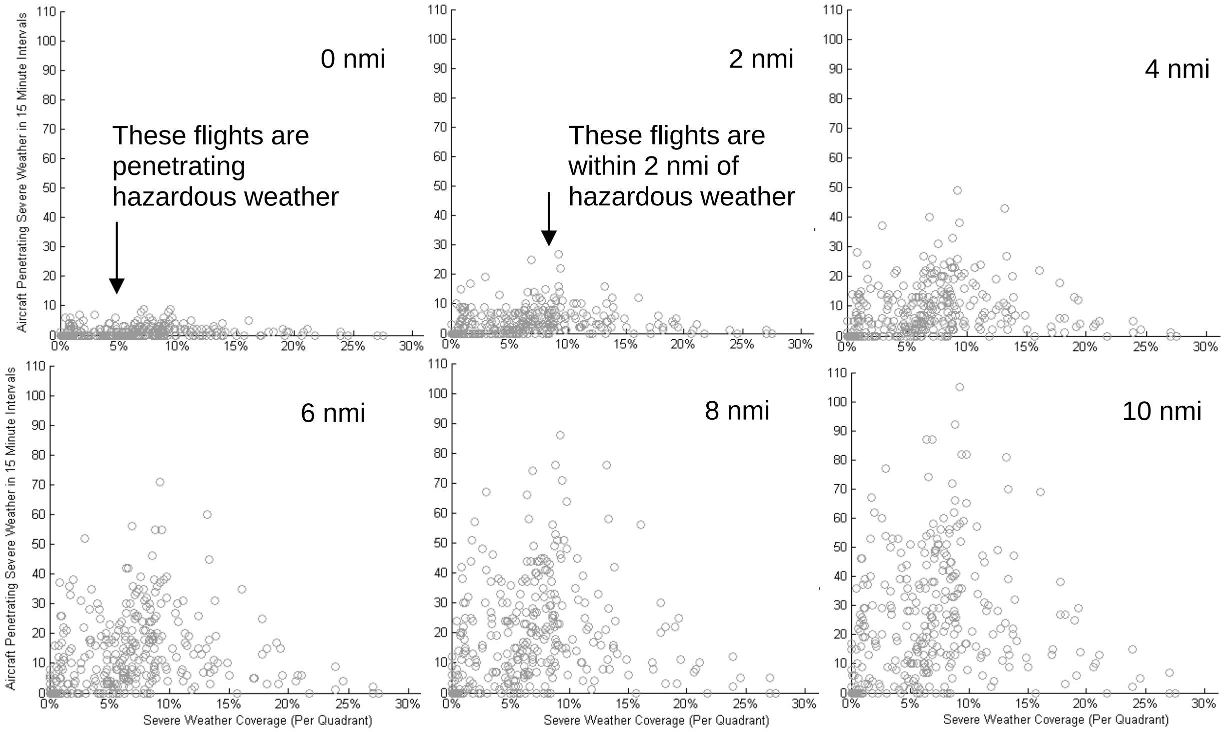


**Figure 8: Clearance from Hazardous Weather based on historical flight data.**

Significant differences in the routing methods occur due to route closures forced by infeasible weather situations. Note in Figure 9 a specific instance where severe weather is located over or just in front of the metering fix and thus this constraint prohibits a flow through the metering fix for the 15-minute time period of the planning time horizon. The performance of both flow-based methods was highly dependent not only on weather severity, but weather cell location. If even a small set of severe weather cells were located directly over the metering fix or over route entry points, then the weather could be sufficient to block all routes connecting to those points.

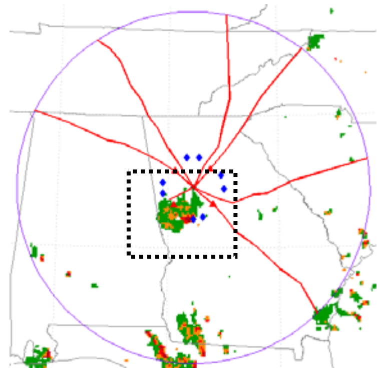

**Figure 9: Route blocked by a small area of hazardous weather (southwest fix).**

The flow-based techniques were tested using varying safety margins for hazardous weather avoidance. With a minimum of 0 nmi weather safety margin (i.e. the flight can get as close to hazardous weather as necessary, but may not penetrate it), there were far fewer route closures. The algorithm performed best under this condition. When increasing the minimum weather safety margin, the throughput decreased, as expected, and delays increased.

Figure 11 and Figure 12 (see next 2 pages) provide example output from the alternate waypoint and FBRP algorithms. Across the board, all of the severe weather avoidance algorithms provided relatively similar average flight times per aircraft. The significant differences in performance arise where the algorithm is not flexible enough to avoid the weather. There are subtle differences for this condition to be met in each of the algorithms. Both methods have some flexibility in where the route entry points are; however, a small portion of hazardous weather at the entry point or the metering fix can have enough impact to render the route unusable. For example, from 12:00 to 17:00 on 6/26/02 (Figure 12), hazardous weather sweeps across the southern metering fixes, blocking all routes first from the southwest then from the southeast.

Flow-based methods show weakness when significantly complex (broadly scattered) weather systems prevent a routable solution. For example, during the period from 18:00 to 23:00 on 6/26/02 (Figure 12) widely scattered storms prevent the routing of flows into the southeastern fix, HUSKY. For these situations there are potential routes available to a smaller subset of aircraft, and in such a case, another method should be used to recover this lost capacity, such as the Free Flight method.

### A. Alternate Waypoints for Variable SIDS and STARS

The alternate waypoint approach is generally the least flexible of the three approaches. When large lines of thunderstorms intersect the base STARs, it is not possible to extend the routes far enough to avoid the hazardous weather (due to the underlying graph structure). Specifically for the overall routes, this is a hindrance because it may be possible for a flow of aircraft to fly around a large storm system. However, close to the metering fix such flexibility in distance is not required. There were cases where small shifts in the metering fix locations could maintain a flow of aircraft into the airport, where a rigid metering fix would have been blocked due to hazardous weather.

### B. Flow-Based Route Planning to the Metering Fixes

The FBRP results demonstrate an increased flexibility in the general routing of flows through the transition airspace. At high levels of severe weather coverage, the FBRP routes are routable, whereas the equivalent Variable STAR routes are not (Figure 16). Breaks in lines are found more frequently than with the Variable STAR approach. The FBRP does, however, show weakness at the endpoints of the routes. When weather impacts the metering fixes, or in some cases the entry points, the routes are designated as un-routable. This explains the slightly weaker performance of the FBRP routes during lower severe weather coverage levels. Periods with moderate weather were sometimes blocked due to scatter weather systems. These could be 'picked through' by individual aircraft, but were not conducive to forming flows (Figure 10).

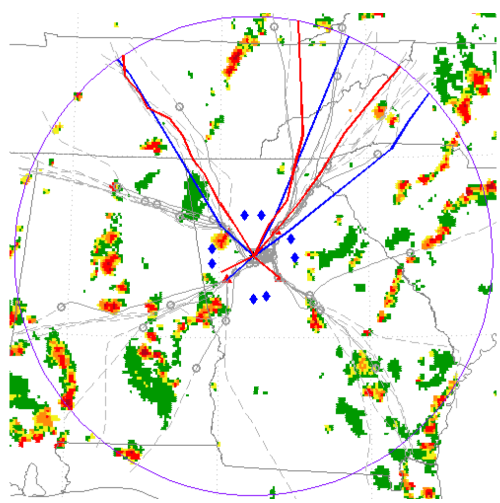

**Figure 10: Historical aircraft 'picking through' hazardous weather from the south.**

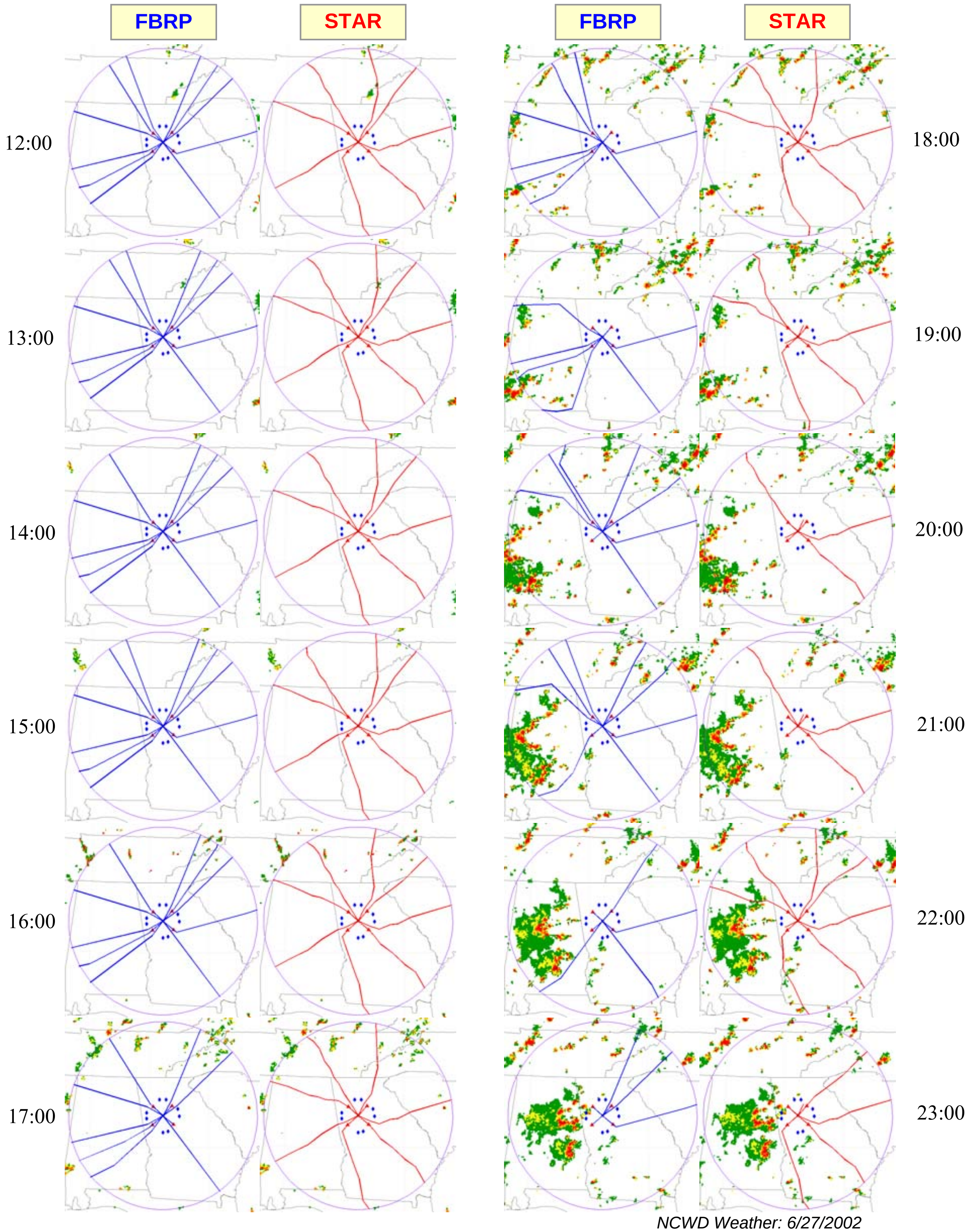


**Figure 11: Comparison of Flow-Based Route Planning to variable STARs to the metering fix for 1 nmi hazardous weather separation with 15-minute update times.**

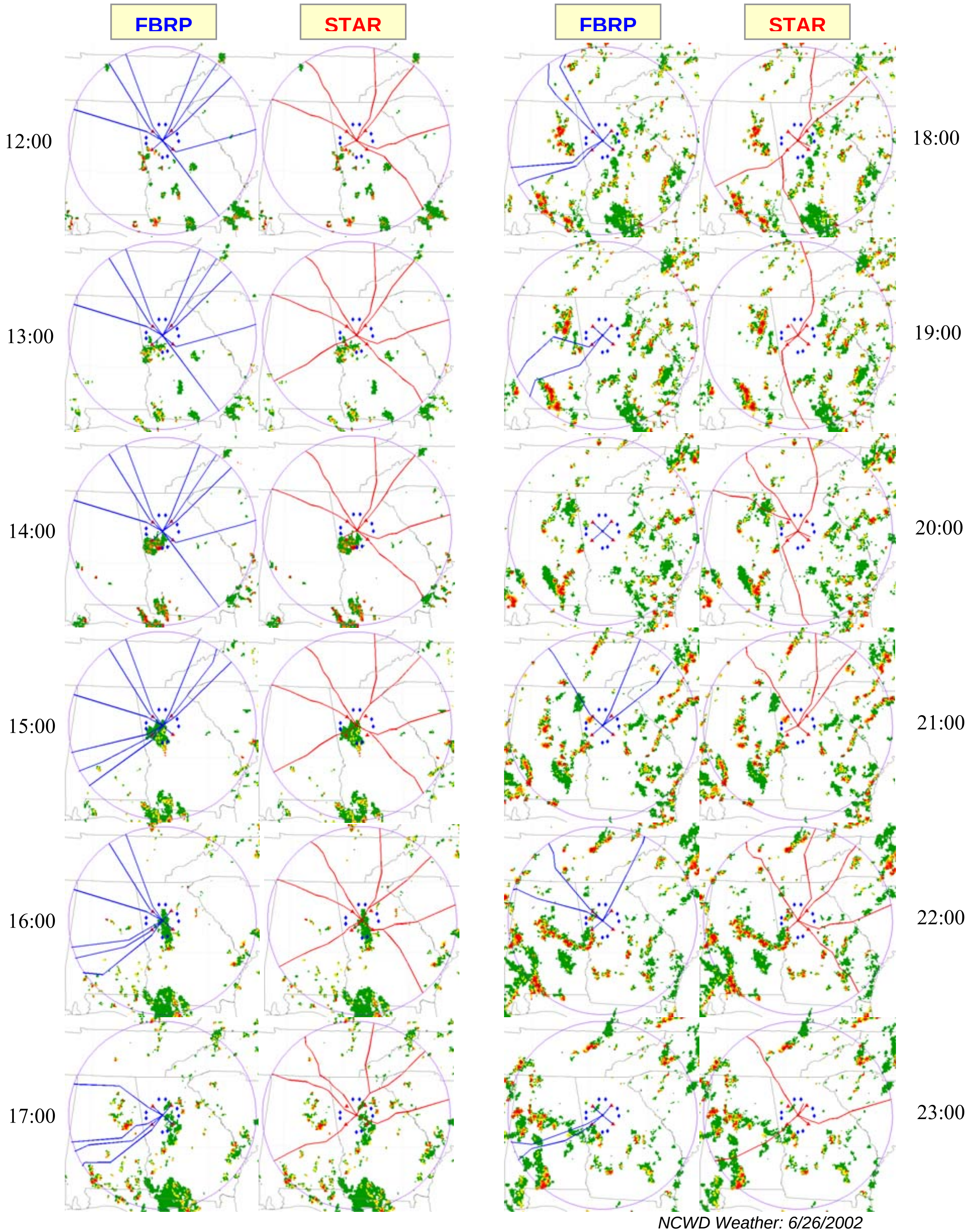


**Figure 12: Comparison of Flow-Based Route Planning to variable STARs to the metering fix for 1 nmi hazardous weather separation with 15-minute update times.**

## C. Free Flight

Intuitively, one would assume a Free Flight solution – a solution with the fewest number of constraints – to always perform better than a flow-based solution. However, this was not the case. In our algorithmic implementation of Free Flight, each flight was "greedily" routed – essentially meaning 'first-come, first-served'. Some solution routes could be particularly efficient while blocking the passage of other flights, resulting in a reduction in performance over a theoretically optimal "unconstrained" solution. Nonetheless, our model of a "greedily" routed set of aircraft is likely to resemble Free Flight where pilots and airlines self-optimize without regard for how their actions might affect others. While a theoretically optimal unconstrained solution should always be at least as good as the flow-based optimal path solution, optimizing the movement of all aircraft individually increases computational complexities and makes the system optimized (as opposed to self-optimized) Free Flight solution impractical.

## D. Comparison

The historical demand was input to the simulation and metric generation. Figure 13 shows the historical throughput measured in 15-minute intervals in each of the quadrants over each experimental period. In essence, each quadrant is considered a separate experiment, as there is little interaction between adjacent quadrants. Figure 14 shows the difference between the historical throughput and simulation throughput. There is little difference. This demonstrates that the historical demand can be managed with the algorithmic approaches and can achieve similar throughput. Note that there are more periods with no throughput. This is a consequence of the safety requirement. By shifting flight schedules and utilizing synthesized routes, safety is improved.

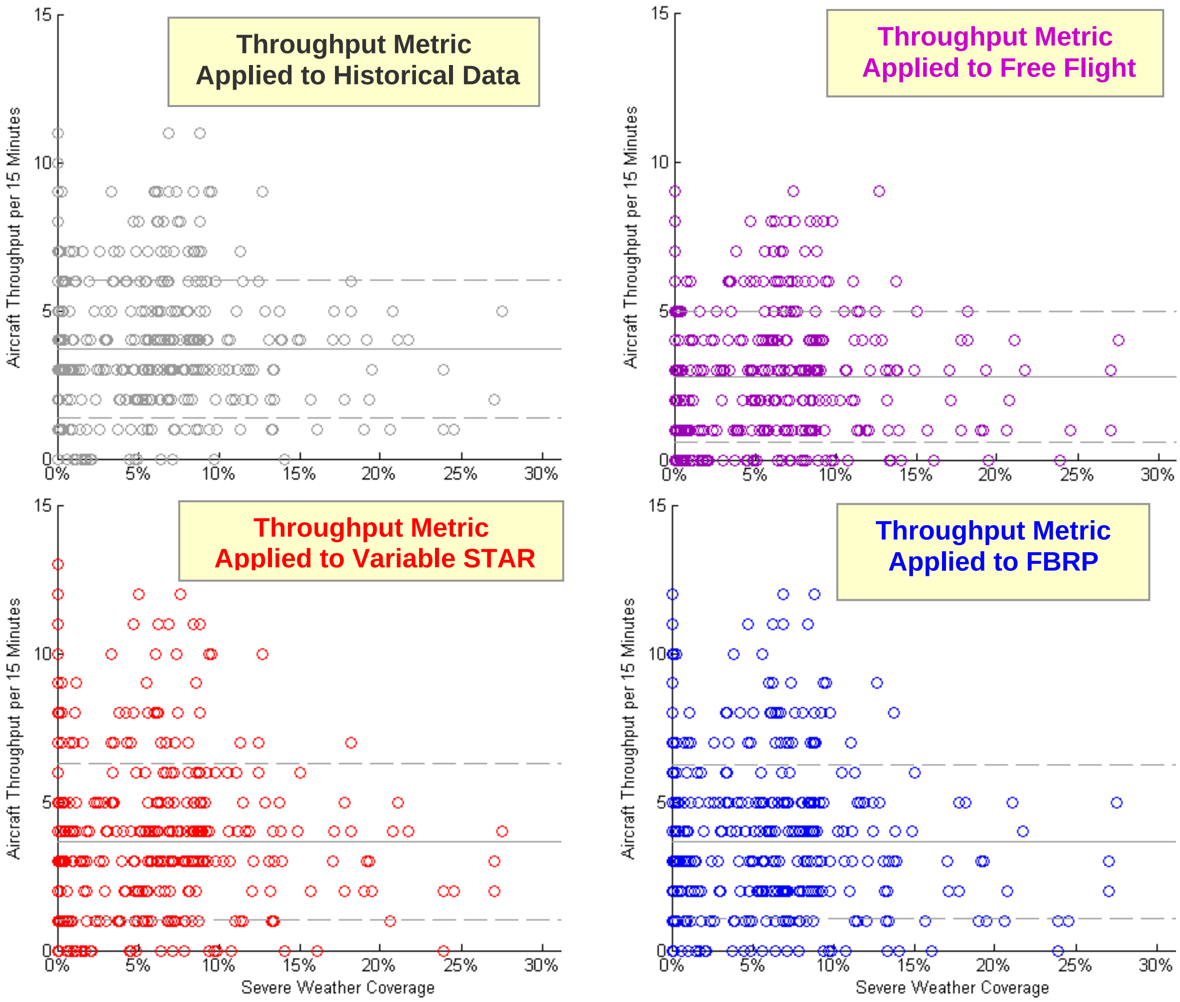


**Figure 13: Comparison of throughput between methods, using 1 nmi weather separation and 15-minute re-planning update times with demand based on historical data.**

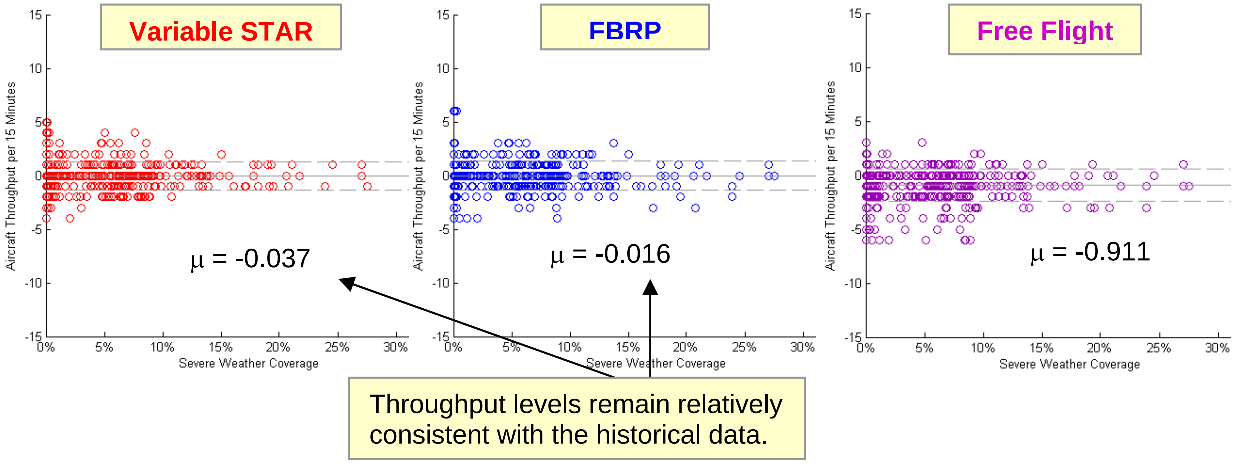


**Figure 14: Comparison of throughput between methods against the historical baseline (method minus baseline), using 1 nmi hazardous weather separation and 15-minute re-planning update times.**

Next, maximum throughput was explored. The different approaches were compared fully utilizing the resources available, with the flow-based techniques providing constant demand at 5 nmi separation over the metering fix, and the Free Flight approach providing as many aircraft as possible at 5 nmi aircraft-to-aircraft separation. The Free Flight approach performed at approximately 80-90% of the flow-based techniques in clear weather.

Figure 15 displays the results of the experiments run with constant demand. The flow-based techniques are either at full throughput, or no throughput, depending on whether there is at least one route open to a particular metering fix. These experiments were useful in identifying how the different methods responded to different weather scenarios. When the throughput reduces to zero, there are no available routes for the respective method. The maximum throughput varies per metering fix and date due to differing speed profiles (the speed profiles were derived from historical data to approximate wind conditions). The results from all experiments displayed in Figure 15 are summarized in Figure 16.

Furthermore, the results from Figure 16 are compared with the historical demand for each of the respective 15-minute intervals. Figure 17 shows this comparison – displaying an overall potential increase in capacity by over 10 aircraft per 15-minutes for each of the methods. That corresponds to over 60 aircraft per hour, per metering fix. This is clearly greater than the overall clear-weather capacity at the airport (approximately 100 aircraft per hour at ATL), but it shows that it is possible to safely attain clear weather capacity during severe weather events, even at greater MIT separation (5 nmi is an absolute minimum; in operations, 5 to 10 MIT are usually used – though this may be reduced in the future with the adoption of more accurate surveillance capability).

Figure 18 shows the difference in the complexity metric measured for each of the algorithmic approaches (using historical demand) compared with the historical data. In all cases, the complexity was reduced. Intuitively, it seems that the complexity of Free Flight should be higher. However, the complexity is dependant in part on the number of aircraft present. Because there were fewer aircraft routed in the Free Flight approach (recall the overall lower throughput in Figure 14), the complexity metric is computed to be lower. This indicates that further complexity metrics should be explored in future research.

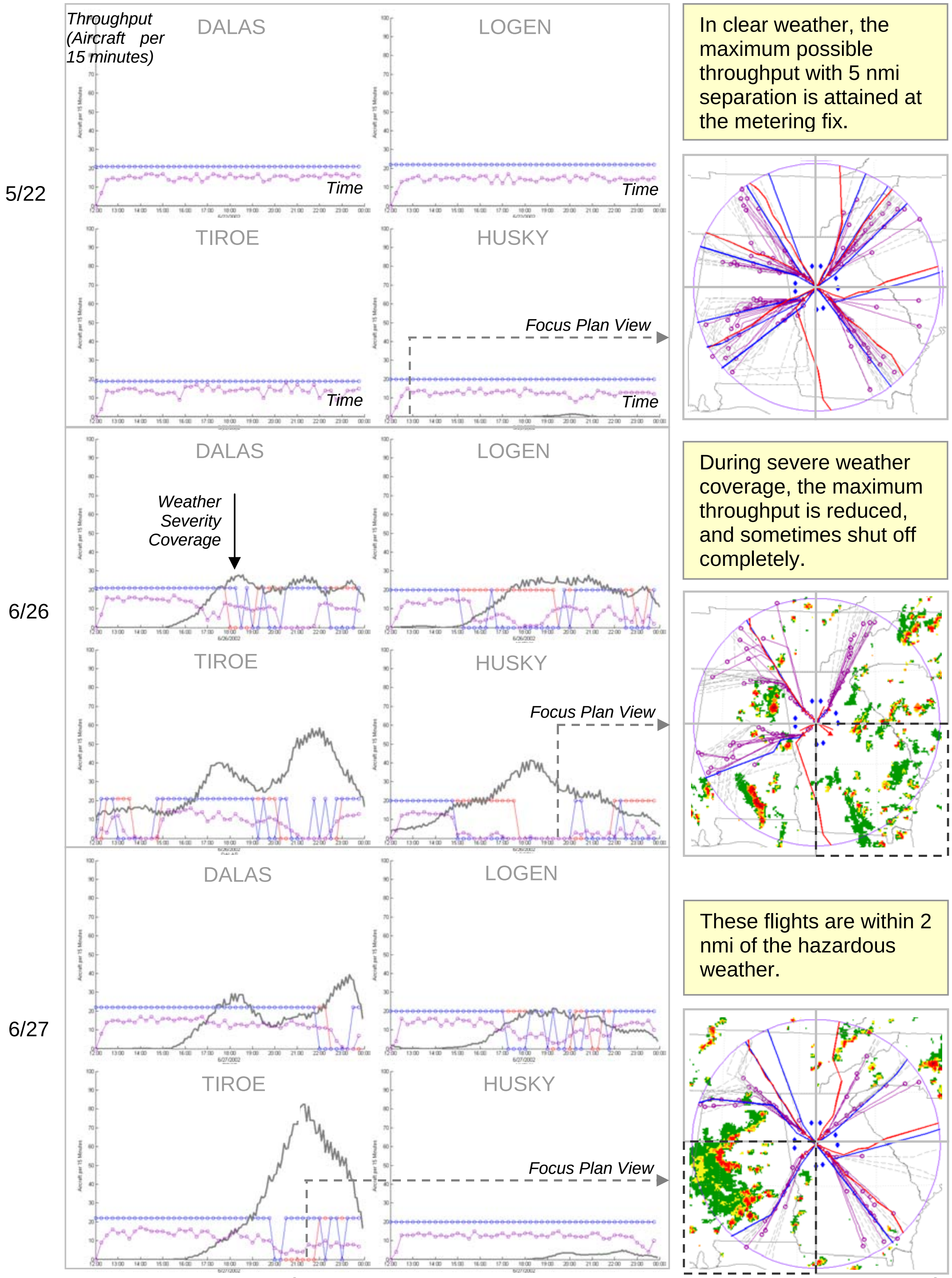


**Figure 15: Comparison of Maximum Throughput attained by each method (reported in aircraft per 15-min), using 1 nmi hazardous weather separation and 15-minute re-planning update times.**

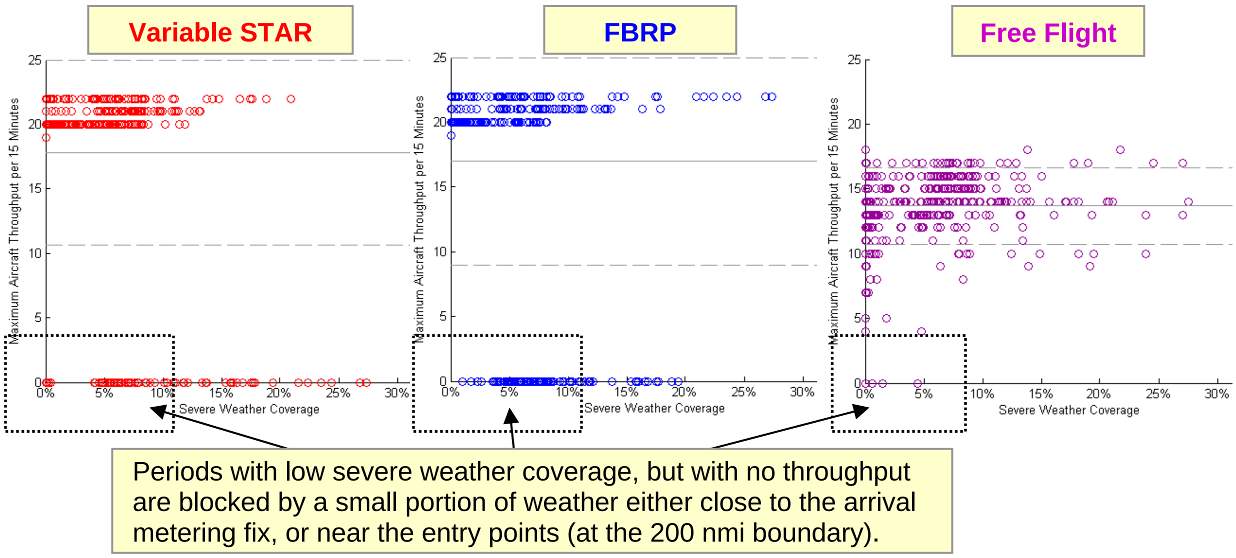


**Figure 16: Maximum Throughput attained over all experiment periods for Variable STARs, FBRP, and Free Flight at a minimum 1 nmi hazardous weather separation.**

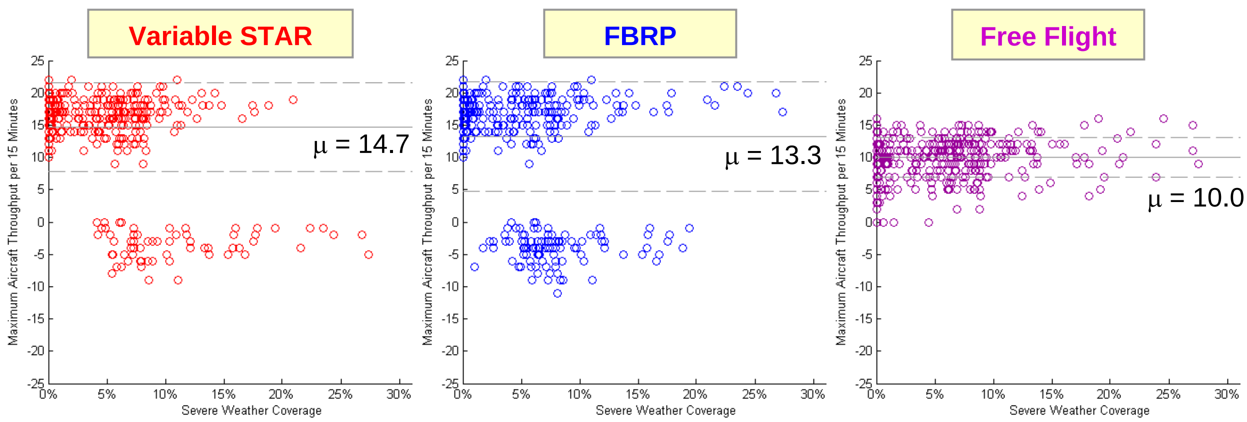


**Figure 17: Potential increase over historical throughput for Variable STARs, FBRP, and Free Flight at a minimum 1 nmi hazardous weather separation.**

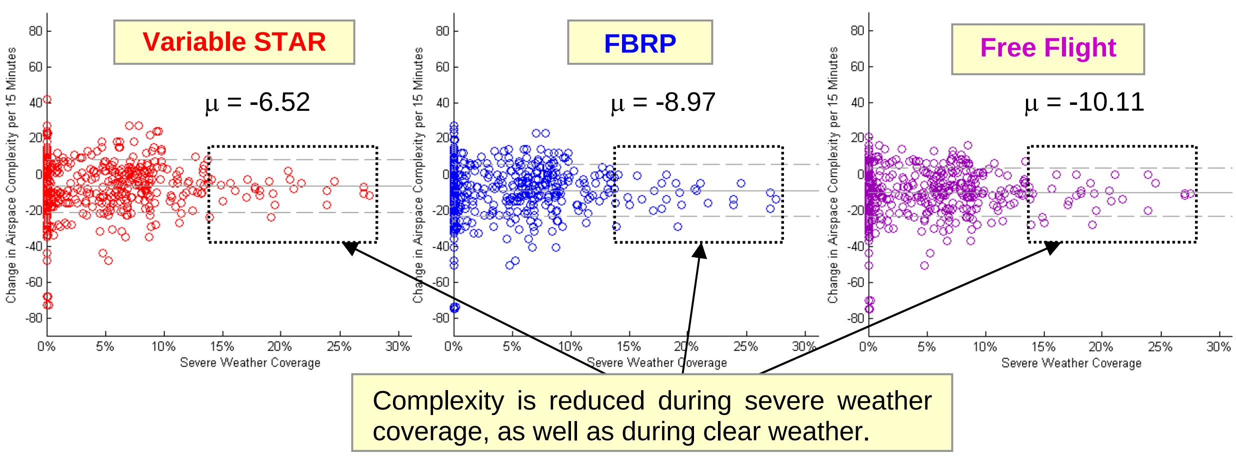


**Figure 18: Comparison of complexity between methods against the historical baseline, using 1 nmi weather separation and 15-minute re-planning update times.**

## Conclusion

Three algorithmic methods have been demonstrated that improve throughput, increase safety, and reduce complexity during hazardous weather events in the transition airspace around an airport. While the general trend is that maximum throughput decreases with increasing weather severity, the specific location of hazardous weather cells plays an important role as well. It is often the proximity of weather to key resources that limits throughput, and therefore overall capacity. This is true for today's existing resources (e.g. the airport, arrival and departure fixes, jet routes, etc.), and was found to be true for conditions within all of the routing algorithms that were included in this study (e.g. entry points and metering fixes). Making these resources flexible and available is the key to maintaining throughput and increasing capacity during severe weather events.

Generally, the Flow-Based Route Planner provides more flexibility than the variable STARs and therefore provides greater throughput. However, when hazardous weather approaches the metering fixes, the variable STARs algorithm results gain some advantage, as this method was designed to adjust the metering fix location to avoid weather. A combination of the methods, applying adjustable metering fixes and entry points to the Flow-Based Route Planner routes should provide a solution that surpasses both techniques.

There is a tradeoff when going from flow-based routes to a Free Flight solution. The flow-based techniques are less computationally intensive, as a single synthesized route may apply to many aircraft. The Free Flight method requires routes to be generated for each aircraft individually that simultaneously avoid hazardous weather and conflicts with all other aircraft. Such a Free Flight solution is expected to be performed on each aircraft in a distributed manner in a self-optimization implementation. In theory, a perfect system-optimized (as opposed to self-optimized) Free Flight solution will always achieve throughput as good, or better, than a flow-based solution, since there are fewer constraints in Free Flight. However, computing such a system-optimized Free Flight solution is infeasible (computationally intractable) with our current algorithms and is not likely to be achieved when each pilot is given the freedom to design his/her own route independent of the other aircraft.

## Future Research

By design, the flow-based algorithms avoid small cells of weather, even when the weather cell is the size of a single pixel. Generally, small weather cells would not affect a jet route, except for minor deviations by aircraft on the route. Indeed, we observe in real-world data that a single small hazardous weather cell may be flown through if near the metering fix of an airport. Future research will address this issue by preprocessing weather data to prevent any singular small cells from affecting route generation.

The weather metric used in this study does not look at the location of the hazardous weather but simply looks at the amount of hazardous weather in the transition airspace. An improved weather metric based on the insights found in this study could provide a better indication of what weather types (shapes, sizes, severity level) adversely affect the transition airspace and its resources (specifically the metering fixes). Better predictions could then be made as to what throughput levels to expect in different types of weather scenarios.

These algorithms may be used with predicted weather and predicted demand on an airport to establish a predicted fix throughput (capacity). Then, the upstream en route traffic flow management could meter traffic such that just enough traffic arrives at the transition airspace to match the transition airspace capacity. If such a process could be performed up to an hour or more ahead of time, even if done with probabilistic traffic demands and probabilistic weather forecasts, then these algorithms may also provide a benefit to designing fix-based ground delay programs, as discussed in the work of Hoffman[15] et al.

Combining multiple airports with overlapping transition airspaces and merging with en route upstream operations are two steps that are necessary for blending the concepts of this study into a feasible operational concept for the NAS. Similar techniques can be applied to the en route airspace to provide flexible resources in that environment as well.

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